125 YEARS AT THE HEART OF ENGINEERING EDUCATION
ASEE
2018 ASEE ANNUAL CONFERENCE & EXPOSITION
JUNE 24–27, 2018
SALT PALACE CONVENTION CENTER
SALT LAKE CITY, UT

Paper ID #21827

Teaching Geometric Dimensioning and Tolerancing Concepts Using 3-D Computer Models and 3-D Printed Parts

Dr. Oziel Rios, University of Texas, Dallas

Dr. Oziel Rios earned his Ph.D. in mechanical engineering from the University of Texas at Austin in 2008 where his research focused on design of robotic systems with an emphasis on kinematic and dynamic modeling for analysis and control. Dr. Rios teaches the first-year and CAD courses in the Mechanical Engineering Department at the University of Texas at Dallas. Dr. Rios has also taught kinematics and dynamics of machines and graduate-level CAD courses. Dr. Rios' research and teaching interests include: robotics, design, kinematics and dynamics of machines and engineering education.

Teaching Geometric Dimensioning and Tolerancing Concepts using 3D Computer Models and 3D Printed Parts

Abstract

Geometric Dimensioning and Tolerancing (GD&T) is an important tool for engineers to efficiently communicate design intent and requirements. GD&T has several advantages including reducing costs by decreasing waste, producing components that are interchangeable, and allows designers to more clearly communicate functional relationships between features in drawings. However, GD&T can be difficult for students to learn due to the visualization skills needed to comprehend the inherent three-dimensional (3D) nature of the geometric tolerance zones. This paper describes an example of how 3D computer models and 3D printed parts made by Fused-Deposition Modeling (FDM) were used to illustrate several GD&T concepts including position tolerance zones, bonus tolerances, datum simulators and priority, and functional gages for part inspection. Since 3D printing technology is becoming more accessible for educators, the method used in this paper can be easily modified, expanded and implemented to teach not only the aforementioned concepts but other GD&T concepts that can be difficult to comprehend. The resources required to implement the example are a computer equipped with Computer-Aided Design (CAD) software and a 3D printer.

1. Introduction

In the Mechanical Engineering Department at the University of Texas at Dallas, students are exposed to 3D CAD modeling during their freshman year [1-3] but are required to take a more intensive CAD course typically taken during the second semester of sophomore year or first semester of their junior year. This CAD course covers 3D part and assembly modeling, parametric curve and surface modeling, fabrication packages for traditional and additive manufacturing, and conventional and geometric tolerancing.

GD&T provides an effective means of specifying nominal part geometry and the allowable variation. The importance of GD&T includes: producing components that are interchangeable, allows designers to more clearly communicate functional relationships between features in drawings, and reduces costs by decreasing waste [4-9]. However, GD&T concepts can be difficult for students to understand not only because of the many symbols and terminology implemented by this graphical language but also because it may be difficult to comprehend the 3D nature of geometric tolerance zones.

In this paper, the design of a functional gage is used to illustrate some GD&T concepts including position tolerance zones, bonus tolerances, and datum simulators and priority. Functional gages are used to check the geometric tolerances of a part when they are specified with the Maximum Material Condition (MMC) modifier [10]. The MMC is “the condition in which a Feature Of Size (FOS) contains the maximum amount of material within the stated limits of size” [11]. A FOS is "one cylindrical or spherical surface, a circular element, a set of two opposed elements or opposed parallel surfaces, each of which is associated with a size dimension" [11]. The Least Material Condition (LMC) is “the condition in which a feature of size contains the least amount of material within the stated limits of size” [11]. For a hole (internal feature), MMC corresponds to the smallest diameter and LMC to the largest. For a shaft (external feature), the opposite is true - i.e., MMC is the largest diameter and LMC the smallest.

For students learning GD&T, it is not only important to create 3D computer models to help visualize the 3D tolerance zones produced by the geometric tolerances but it is also important to use a functional gage (physical tool) to check if a part is within the specified variation. A functional gage has the additional advantage that it is easy to implement. However, fabricating a functional gage can be expensive and the gage must be reworked if the part drawing changes. Creating a 3D printed functional gage can overcome these cost limitations.

In the rest of this paper, the calculations necessary to define the size of the functional gage and to understand the bonus tolerances that result when the part deviates from its MMC condition are presented. A description of the 3D computer model and 3D printed functional gage and parts are also presented. Finally, the results of a survey administered to students at the end of the semester are provided.

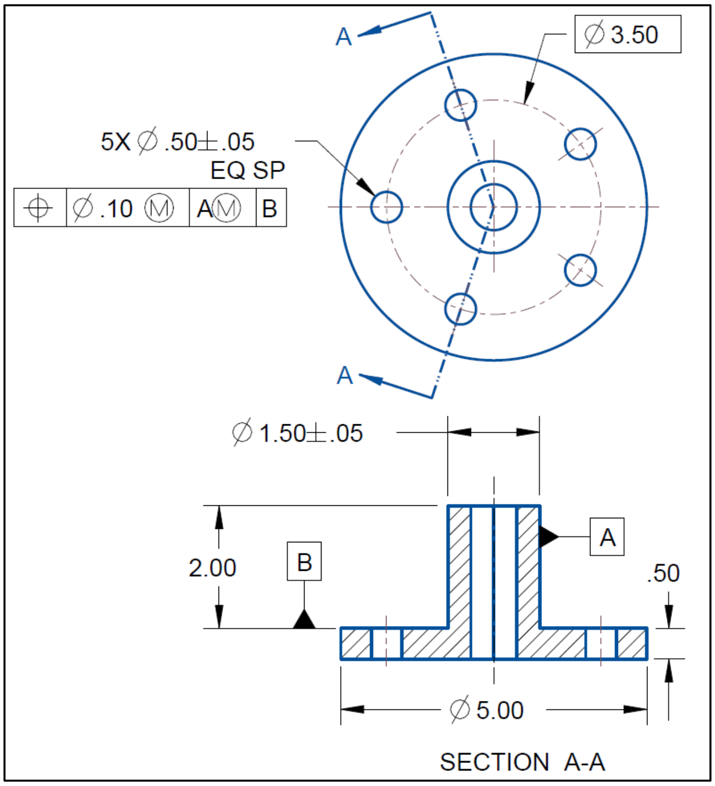


Figure 1. The component with a circular hole pattern dimensioned in units of inches. Dimensions and tolerances of some features are not shown for clarity.

2. Description of the Problem

In this problem, a functional gage to inspect a circular hole pattern of the component shown in Figure 1 is designed. The objective was to teach the concepts of position tolerance zones, datum simulators, MMC and LMC conditions, and bonus tolerances. This problem was used as an example taught to a class of 45 students in the Fall 2017 semester and took approximately 3 hours of class time to complete. Prior to working on this problem, 6 hours of engineering drawings and 6 hours of conventional and geometric tolerancing were presented during lecture. Some topics covered during these lectures included the use of model views including cross-section and auxiliary views, the use of symbols, dimensioning a drawing, types of tolerances, key terms including MMC, LMC and FOS, and allowance calculations. The rest of this section explains how the calculations were presented in lecture.

To begin, it is assumed the size tolerances of the holes and the cylindrical surface A have been verified to be within tolerance. The goal of this problem is to determine if the location of the hole pattern is within tolerance. Additionally, the tolerances were purposely chosen to be large in value for illustration purposes and to ensure the 3D printer would fabricate the parts satisfactorily. Real-world applications may implement smaller tolerance values but the reasoning and calculations involved would be the same.

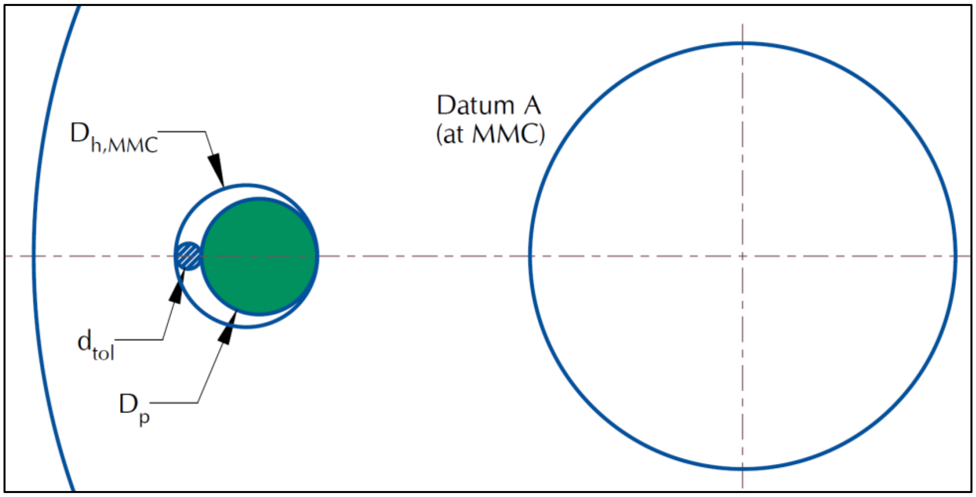


Figure 2. Diagram used to determine functional gage pin diameter.

2.1 Determining Gage Pin Diameters

The hole positions can be verified to be within tolerance using a functional gage with five pins whose locations are given by the basic dimensions specified in the drawing of Figure 1. The diameters of the pins are determined first. In the feature control frame, the hole locations are toleranced relative to the MMC size of the hole and the MMC size of the cylindrical datum A. The MMC of the hole (internal FOS) is $\phi 0.45\ in$ and the MMC of datum A (external FOS) is $\phi 1.55\ in.$

Next, referencing the diagram of Figure 2 which shows the top-view of the features and tolerance zone, the pin diameter of the functional gage, D_p, is determined to be

$$\begin{aligned} D_p &= D_{h,MMC} - d_{tol} \\ &= \phi 0.45\ in - \phi 0.10\ in \\ &= \phi 0.35\ in \end{aligned} \tag{1}$$

In Equation 1, $D_{h,MMC}$ and d_{tol} are the diameters of the hole size at MMC and position tolerance size specified in the feature control frame, respectively. Figure 5 shows the functional gage designed using the pin diameter calculated above with locations specified by the basic size in drawing of Figure 1.

2.2 Investigating Bonus Tolerances

The bonus tolerance of the position tolerance zone is investigated when the part deviates from the MMC values. This was addressed incrementally in two cases:

I) Hole at LMC and datum A at MMC
II) Hole and datum A at LMC

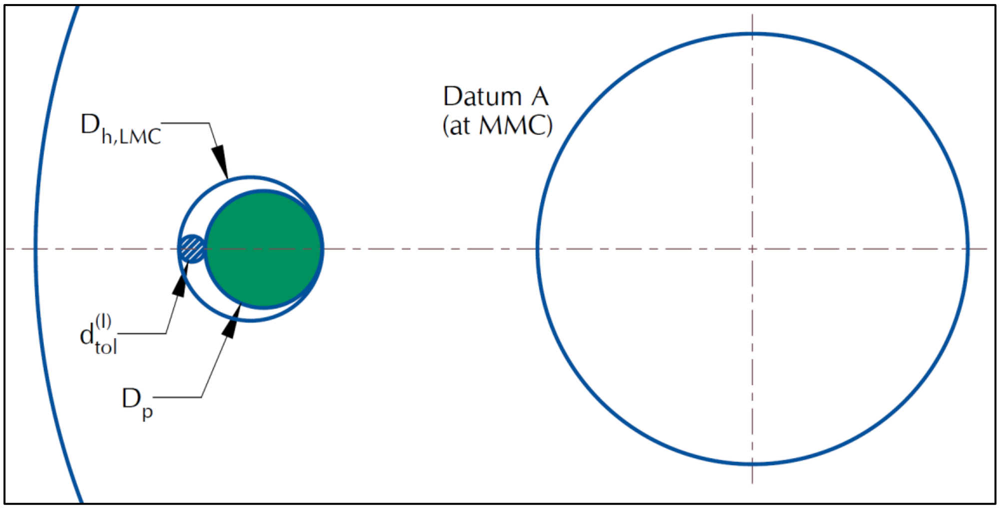


Figure 3. Diagram used to determine position tolerance for Case (I).

The scenario of Case (I) is detailed in Figure 3. In this case, the allowable variation of hole position, $d^{(\mathrm{I})}_{tol}$, is

$$\begin{aligned} d^{(\mathrm{I})}_{tol} &= D_{h,LMC} - D_p \\ &= \phi 0.55\ in - \phi 0.35\ in \\ &= \phi 0.20 in \end{aligned} \tag{2}$$

where $D_{h,LMC}$ is the diameter of the hole at LMC. Hence, the bonus tolerance for Case (I), $d^{(\mathrm{I})}_{bonus}$, is

$$\begin{aligned} d^{(\mathrm{I})}_{bonus} &= d^{(\mathrm{I})}_{tol} - d_{tol} \\ &= \phi 0.20\ in - \phi 0.10\ in \\ &= \phi 0.10\ in \end{aligned} \tag{3}$$

Since the position tolerance size is defined relative to the hole's MMC condition, when the hole size deviates from it's MMC value a bonus tolerance results up to $\phi 0.10\ in$.

The scenario of Case (II) is detailed in Figure 4. In this case, the additional variation of the cylindrical surface A, $d_{A,var}$, needs to be taken into account. This is determined as follows:

$$\begin{aligned} d_{A,var} &= d_{A,MMC} - d_{A,LMC} \\ &= \phi 1.55\ in - \phi 1.45\ in \\ &= \phi 0.10\ in \end{aligned} \tag{4}$$

where $d_{A,MMC}$ and $d_{A,LMC}$ are the MMC and LMC values of datum A, respectively. The allowable variation of the hole position is now

$$\begin{aligned} d_{tol}^{(\mathrm{II})} &= D_{h,LMC} + d_{A,var} - D_p \\ &= \phi 0.55\ in + \phi 0.10\ in - \phi 0.35\ in \\ &= \phi 0.30 in \end{aligned} \tag{5}$$

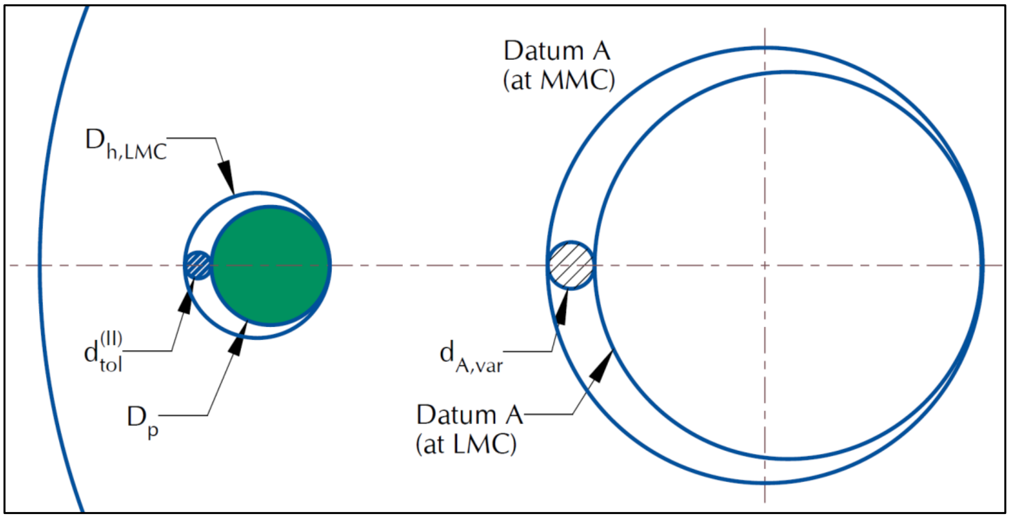


Figure 4. Diagram used to determine position tolerance for Case (II).

This yields a bonus tolerance of

$$\begin{aligned} d_{bonus}^{(\mathrm{II})} &= d_{tol}^{(\mathrm{II})} - d_{tol} \\ &= \phi 0.30\ in - \phi 0.10\ in \\ &= \phi 0.20\ in \end{aligned} \tag{6}$$

Hence, when the hole size and cylindrical surface A deviate from their MMC values, the allowable variation of the hole size is up to 3 times the position tolerance specified by the designer in the feature control frame. Table 1 shows the total and bonus tolerances that result for different hole and surface A sizes. The top row of this table corresponds to the hole and surface A at their respective LMC values and the last row to their respective MMC values. It should be noted that the last three rows correspond to Case (I) where the datum A is at its MMC value.

Table 1. Total and bonus tolerance values for different hole and surface A sizes. All values in inches.

D_h	d_A	$d_{tol}^{(\mathrm{II})}$	$d_{bonus}^{(\mathrm{II})}$
0.55	1.45	0.30	0.20
0.50	1.45	0.25	0.15
0.45	1.45	0.20	0.10
0.55	1.50	0.25	0.15
0.50	1.50	0.20	0.10
0.45	1.50	0.15	0.05
0.55	1.55	0.20	0.10
0.50	1.55	0.15	0.05
0.45	1.55	0.10	0.00

Since MMC condition is typically implemented in drawings when components are to be fabricated using conventional subtractive manufacturing techniques/tools to reduce scrap, the bonus tolerance should be determined and the functional requirements of the component should be assessed with this additional allowance in variation.

3. 3D Computer Model

The 3D computer model of the functional gage designed for this application is shown in Figure 5. It is assumed the variation of the simulated cylindrical datum A and planar datum B are much less compared to the variation of the surfaces of the part making contact with the simulated datums of the functional gage.

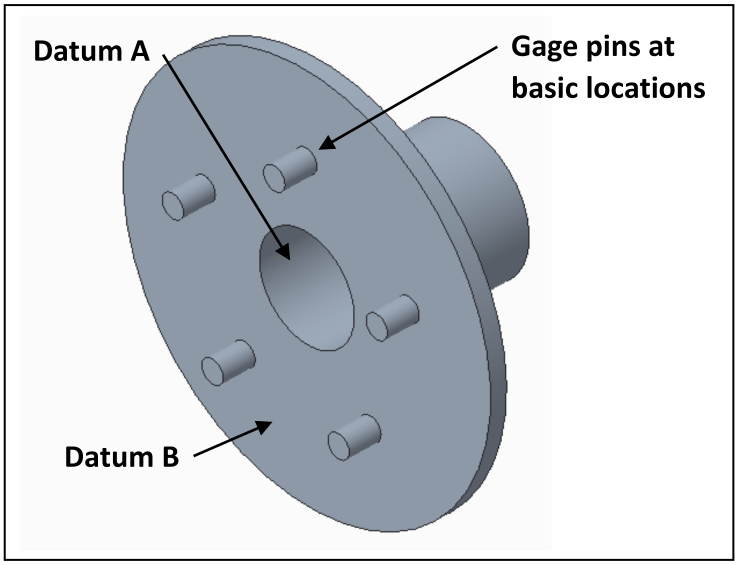


Figure 5. The functional gage designed for this application with simulated datums A (cylindrical) and B (planar).

Additionally, a 3D model of a 'bad' part is created. For this part, the cylindrical surface A is at its MMC value ($\phi 1.55\ in$) and all five holes have size $\phi 0.50\ in$ – the basic size. Four holes are located at their basic size while the fifth hole is at a distance of $\phi 3.70\ in$ (diameter) from axis of

A. For the feature sizes in Table 1, the hole location should be at most at a distance of $\phi 3.65\ in$. The error in hole location cannot be visually detected but upon creating the computer model, the interference between the gage pin and hole is evident (see Figure 6).

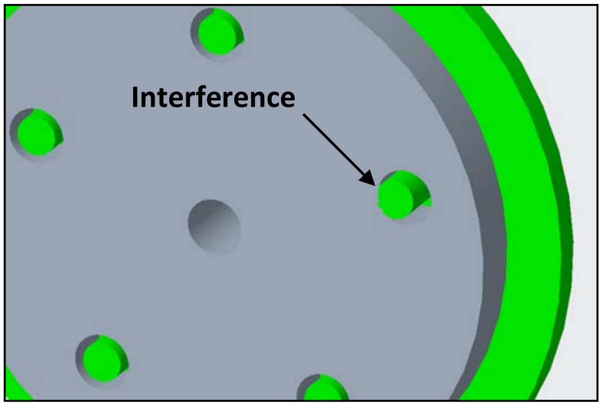
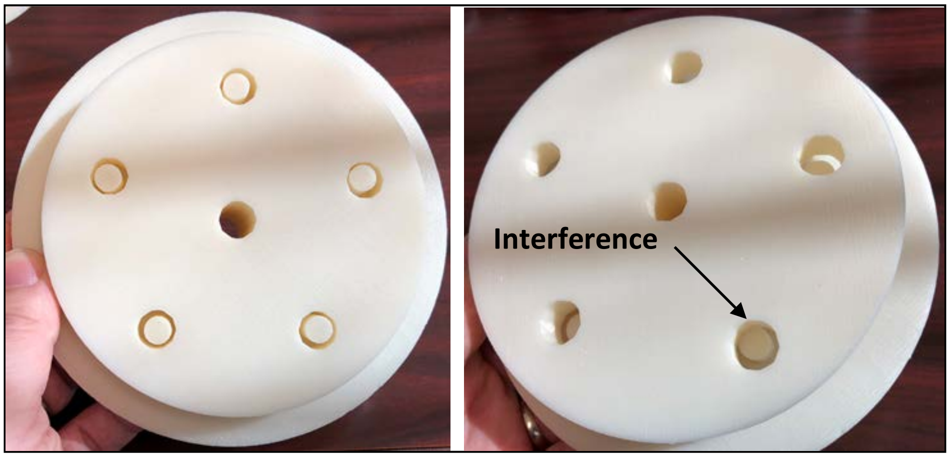


Figure 6. Computer model showing interference of gage pin with 'bad' part.

4. 3D Printed Parts

A 3D printer was used to fabricate the functional gage and 'bad' part previously discussed. Additionally, a 'good' part was also printed where surface A was set to $\phi 1.50\ in$, the hole sizes were $\phi 0.50\ in$ and the location of all holes were at the basic size $\phi 3.50\ in$.

The 3D printed functional gage and parts were fabricated out of ABS using a Dimension Elite 3D printer with a layer thickness of $0.007\ in$. This 3D printer implements FDM with support material removal [12]. Also, the best practices discussed in [13] are implemented when setting up the 3D model for printing. Since the sizes and tolerances implemented were large compared to the layer thickness, the components and functional gage performed as intended and did not deform when the inspection procedure was performed. Also, to the author's eye there was no visual difference between the 'good' and 'bad' 3D printed parts.



(a) (b)

Figure 7. 3D printed parts and functional gage used to determine (a) the 'good' part and (b) the 'bad' part.

The 3D printed functional gage and parts were passed out to the students during lecture. The students were shown how to check the parts implementing the datum priority set in the feature control frame. Reading the feature control frame, we see that in order to check the hole positions we have to establish contact with the cylindrical datum A followed by contact with the planar datum B. Following this procedure, the students easily identified the ‘good’ and ‘bad’ parts as shown in Figure 7.

Next, the students were asked to ignore the datum priority and only establish contact with planar datum B. In this scenario, both parts pass inspection. Figure 8 shows how the 'bad' part can pass inspection when datum priority is not followed. This was surprising to the students and reinforced the importance of following the datum priority established by the feature control frame.

Figure 8. ‘Bad’ part passes inspection when datum priority not followed.

5. Methods and Results

Students were asked to provide anonymous feedback on the activity in a survey administered at the end of the course. The survey includes the student's perception of their understanding of the topics covered and if the 3D printed components and functional gage helped them understand some of these topics. The students were asked to respond to the following statements based on a 5-point Likert scale where a value of 1 meant they strongly disagreed with the statement and a value of 5 meant that they strongly agreed.

1) I understand why the geometric tolerances controlling position require the use of datums.
2) I understand why a bonus tolerance can result when position geometric tolerances and MMC are applied.
3) I understand why a functional gage can be used to check position geometric tolerances at MMC.
4) The 3D printed components and functional gage shown in class helped me understand the concept of bonus tolerance.
5) The 3D printed components and functional gage shown in class helped me understand how a functional gage can be used for part inspection.

The results of these are plotted in a diverging staked bar chart [14] as shown in Figure 9. The raw data is given in Table 2. Out of 45 students in the class, 28 students responded to the survey and allowed their anonymous responses be used for research purposes.

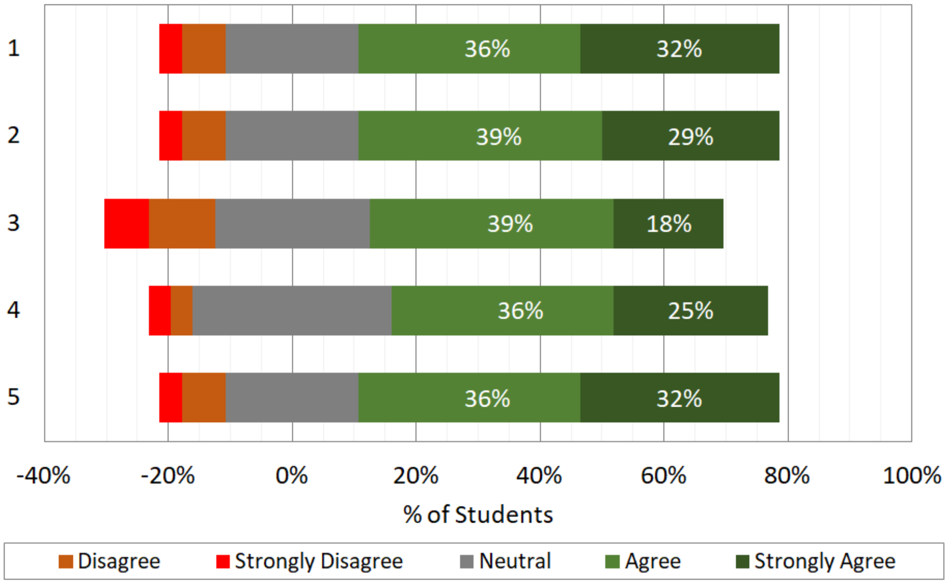


Figure 9. Student responses to survey questions.

Table 2. Number of students who strongly disagree (SD), disagree (D), agree (A), strongly agree (SA) and where neutral (N) with the statements.

Statement	SD	D	N	A	SA	Total
1	1	2	6	10	9	28
2	1	2	6	11	8	28
3	2	3	7	11	5	28
4	1	1	9	10	7	28
5	1	2	5	12	8	28

As can be seen from Figure 9, over 57% of the students who responded to the survey either agreed (A) or strongly agreed (SA) with each of the statements.

Students were also asked to provide free-response comments on the difficulties they faced learning about geometric tolerances. Some students could have benefited from more lectures (only an introduction is intended in this course): "need more practice," and "not solving enough problems." Some students had difficulty understanding the tolerance zones: "the shape of tolerance zone," and "location tolerances." A student mentioned difficulty with "all the symbols and their meanings." Some students explained they benefited from the examples: "I think it was hard visualizing this but the examples helped," and "lecture slides and examples were helpful." After reviewing the student's comments and positive feedback on the example with 3D printed parts, introducing more examples like this would be greatly beneficial. To this end, more examples with detailed calculations, diagrams, 3D models, and 3D printed parts will be created for future semesters.

6. Conclusions

In this paper, an example problem to illustrate GD&T concepts using 3D models and 3D printed parts was described. The example is considered simple to implement only requiring CAD software and a 3D printer and was successfully administered to 45 students. Results from a student survey (28 respondents) indicate the example had a positive effect on the student's understanding of the concepts including position tolerances, bonus tolerances, and using a functional gage for part inspection. The approach presented in this paper can easily be expanded to address other topics of GD&T and it can be easily administered at other educational institutions.

7. Acknowledgement

The author would like to thank Dr. Dani Fadda for his support of this work.

8. References

[1] Rios, O. and Fadda, D., "A Mechanical Engineering Activity-Based Freshman Course," Proceedings of the ASME IMECE, Tampa, Florida, 2017.
[2] Rios, O. and Fadda, D., "A First-Year Design-Based Activity for Mechanical Engineering Students," Proceedings of the ASEE Gulf-Southwest Section Annual Conference, University of Texas at Dallas, Richardson, Texas, 2017.
[3] Rios, O. and Fadda, D., “A Conceptual Mechanism Design Activity for an Introduction to Mechanical Engineering Course,” Proceedings of the ASEE Gulf-Southwest Section Annual Conference, University of Texas at Austin, Austin, Texas, 2018.
[4] Lin, C., Verma, A., "Clarifications of Rule 2 in Teaching Geometric Dimensioning and Tolerancing," Proceedings of the ASEE Annual Conference and Exposition, Honolulu, Hawaii, 2007.
[5] Waldorf, D. J., Georgeou, T. M., "Geometric Dimensioning and Tolerancing (GD&T) Integration Throughout a Manufacturing Engineering Curriculum," Proceedings of the ASEE Annual Conference and Exposition, New Orleans, Louisiana, 2016.
[6] Paige, M. A., Fu, K., "Spatial Demonstration Tools for Teaching Geometric Dimensioning and Tolerancing (GD&T) to First-Year Undergraduate Engineering Students," Proceedings of the ASEE Annual Conference and Exposition, Columbus, Ohio, 2017.
[7] Sriraman, V., De Leon, J., "Teaching Geometric Dimensioning and Tolerancing in a Manufacturing Program," Journal of Industrial Technology, Vol. 15, No. 3, 1999.
[8] Yip-Hoi, D. M, Gill, D., "Use of Model-Based Definition to Support Learning of GD&T in a Manufacturing Engineering Curriculum," Proceedings of the ASEE Annual Conference and Exposition, Columbus, Ohio, 2017.
[9] Narang, R., "Teaching Applied Measuring Methods Using GD&T," Proceedings of the ASEE Annual Conference and Exposition, Pittsburgh, Pennsylvania, 2008.

[10] Lin, C. Y., Moustafa, M., "A Template Functional-Gage Design Using Parameter-File Table in Autodesk Inventor," Proceedings of the ASEE Annual Conference and Exposition, Portland, Oregon, 2005.
[11] Meadows, J. D., "Geometric Dimensioning and Tolerancing: Applications, Analysis & Measurement [per ASME Y14.5-2009]," James D. Meadows & Associates, Inc. and ASME Press, 2009.
[12] www.stratasys.com, "Dimension Elite User Guide," Document #204400-0002, 2007.
[13] Ameta, G., Lipman, R., Moylan, S., Witherell, P., "Investigating the Role of Geometric Dimensioning and Tolerancing in Additive Manufacturing," Journal of Mechanical Design, Vol. 137(11), 2015.
[14] Robbins, N. B., Heiberger, R. M., "Plotting Likert and Other Rating Scales," Joint Statistical Meeting, Section on Survey Research Methods, 2011.